GEOCHEMICAL EXPLORATION OF A "DIFFICULT GEOTHERMAL SYSTEM, PARASO, VELLA LAVELLA, SOLOMON ISLANDS

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ABSTRACT- Thermal activity at the Paraso geothermal field, Vella Lavella, Solomon Islands, consists largely of steam-heated features, usually associated with vapor-dominated zones of a geothermal system. Chloride contents of up to 2400 mg/kg in some of the waters, however, point to the simultaneous discharge of waters from liquid-dominated parts of the system. Varying contamination of the neutral Cl waters with the steam-heated, acid waters greatly impedes application of standard solute geothermometers; only K/Na ratios provide an indication for the occurrence of high temperatures of 290°C at depth. Gas geothermometers (CO_2, CH_4, H2) are more reliable and confirm deep temperatures of close to 300°C. The isotopic composition of the high Cl waters corresponds to an ^{18}O-shift of *6‰* or the presence of about 40% of "andesitic water". The isotopic composition of H_2S ($\delta^{34}S = 0‰$) and low CO_2/He (75 000) and N_2/He (450) ratios, however, suggest a largely mantle origin, only little contaminated by volatiles from subducted sediments. The simultaneous discharge of fluids representative of vapor-and liquid-dominated zones is likely to be due to the Paraso field being situated in a narrow valley, at close to sealevel, preventing clear separation of vapor- and liquid-dominated discharge features.

Key Words: Paraso geothermal field; Solomon Islands; geothermal waters; geothermal gases; geothermometers

1. INTRODUCTION

Vella Lavella, an island about 40 km long (NW-SE) and 20 km wide, is the northernmost in the New Georgia group of the Solomon Islands. It consists largely of basaltic to andesitic rocks (Taylor, 1976); limestone and raised coral reefs are found in the south. According to Furumoto *et al.* (1970), the crust is exceptionally thin there, with the mantle lying a at depth of only 8 km. Discharge of thermal fluids is restricted to an area of about 2 km^2 marked by anomalous or absent vegetatation. Several hot pools, however, are found in regions of normal bush (Fig. 1). The thermal features extend for about 2 to 4 km inland from Paraso Bay and lie about 20 to 50 m above sealevel in a valley within the Vella Graben (Taylor, 1976). The area is drained by the Ulo River passing through the thermal area and merging with the Ngkosole River to the NE.

Earlier chemical results for water samples from hot springs and mud pools of the area were reported by Glover (1975) and Taylor (1976). The main aim of the visit in March 1977 was the collection of additional water and gas samples, for both chemical and isotopic analysis, in order to asses the potential of the Paraso field for geothermal power production.

A preliminary evaluation (Giggenbach, 1978) of the chemical and isotopic results showed that the waters represent mixtures of high Cl (up to 2340 mg/kg) and SO4 waters in highly variable proportions, with no clear trends thus preventing ready identification of endmember components or of deep water/rock equilibration conditions on the basis of geochemical techniques available then. The chemical and isotopic compositions of the gases were quite uniform and pointed to the existence of a vapor-, if not "gas-" dominated system, a finding in apparent conflict with the discharge of high Cl waters. Since 1978, the arsenal of geochemical techniques for the interpretation of the compositions of geothermal water and gas discharges has increased considerably, and it appeared worthwhile to apply some of these to an apparently geochemically quite "difficult" system.

2. CHEMICAL COMPOSITION OF WATERS

The chemical compositions of water discharges from thermal pools, of rivers and seawater, together with measured discharge temperatures, are given in Table 1. Sampling positions are shown in Fig. 1. Four sub-areas, A to C, are distinguished: all contain vigorously "boiling" pools, but with temperatures generally well below local boiling point. In these cases, ebullition is largely caused by the passage of gas rich vapors, rather than flashing of steam. Large areas of diffuse, but vigorous gas discharge through a thin, surficial layer of water are called "sizzling flat". The three river samples represent the composition of Ulo River upstream of the thermal area, the remaining two the composition of both Ulo and Ngokosole Rivers downstream of the main thermal area.

An initial classification of the waters is carried out on the basis of relative contents of the three major anions, Cl, SO4 and HCO_3, as shown in Fig. 2. All the neutral, comparatively high Cl waters plot close to the Cl corner of the diagram, but somewhat outside the field designated "mature waters" (Giggenbach, 1991). The position of the data points would be compatible with the addition

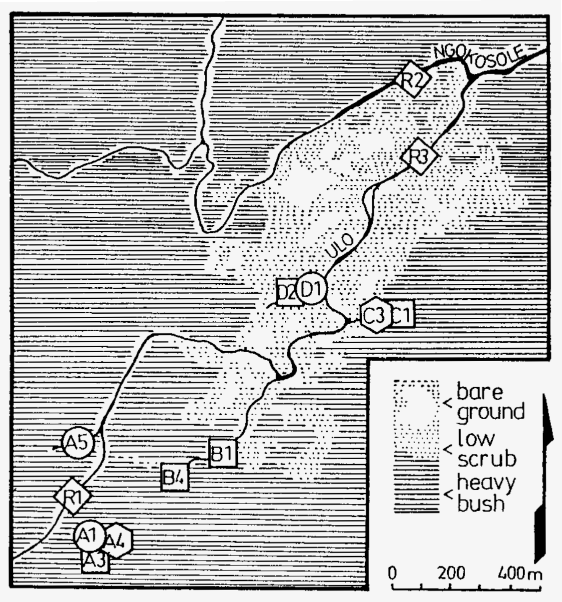

Figure 1 Sketch map of the Paraso geothermal area. For symbols see Table 1 and Fig. 2.

Table 1 - Chemical composition, in mg/kg, and discharge temperatures, in °C, of waters from the Paraso Geothermal Field.

No	t(°C)	pH	Li	Na	K	Rb	Mg	Ca	B	HCO_3	SiO_2	SO_4	Cl	ref
A1	83	5.5	0.55	422	83	0.33	11.0	97	15	-	65	150	853	a
A2	92	5.5	0.54	469	91	0.40	14.0	132	10	24	72	85	999	**b**
A3	92	2.9	0.17	136	27	0.08	11.1	51	5	-	81	300	295	a
A4	30	7.4	<.01	12	2	0.01	7.6	17	3	72	53	15	30	a
A5	46	6.9	0.69	447	74	0.34	28.0	105	3	134	88	45	937	a
B1	39	3.3	0.01	18	4	0.01	7.5	15	2	-	64	120	28	a
B2	-	2.3	0.02	23	16	<.01	24.0	44	-	-	280	666	6	**b**
B3	-	6.1	0.06	133	23	0.01	5.8	20	2	7	80	83	209	**b**
B4	97	2.8	<.01	9	3	<.01	10.0	17	2	-	97	415	2	a
C1	92	3.2	0.02	36	5	0.01	18.8	38	15	.	106	320	33	a
C2	92	3.8	0.10	80	11	0.10	33.0	98	30	-	176	390	110	**b**
C3	93	7.0	0.14	118	12	0.02	5.9	18	4	110	118	90	111	**a**
C4	90	6.9	0.31	282	16	0.10	6.2	53	8	60	170	110	374	**a**
D1	56	5.6	1.82	1207	178	0.74	26.6	289	16	6	150	205	2340	a
D2	-	-	1.20	781	111	-	15.0	190	-	-	129	150	1550	c
D3	86	4.1	0.47	272	31	0.11	42.8	167	5	-	295	570	500	a
R1	30	7.3	0.08	52	9	0.02	9.2	20	<2	81	53	22	106	a
R2	27	7.0	0.12	72	14	0.04	5.7	24	<2	62	48	18	156	a
R3	34	7.0	0.19	127	19	0.07	12.7	40	<2	50	64	47	256	a
R4	32	7.5	-	150	17	-	13.9	42	-	27	57	63	263	c
SW	-	-	0.10	10760	390	0.20	1290	410	I	140	1	2710	19350	

a. This work b. Glover (1975) c.- Taylor (1976)

of seawater (SW). Low pH, SO_4 rich waters plot along the Cl-SO_4 axis, some over a range earlier designated "volcanic waters", typical of the direct absorption of volcanic vapors into groundwater (Giggenbach, 1991). Such volcanic waters, as represented by those of volcanic crater lakes, are usuall highly acidic. In the present case, the intermediate Cl-SO_4, only weakly acid waters are more likely to represent mixtures of Cl waters and high SO4 waters resulting from the absorption and oxidation of H_2S in steam-heated pools, as represented by samples B2 and **B4.** Only samples A4 and C3 contain HCO_3 as the predominant anion. SO_4/Cl ratios of the river waters are similar to those of the Cl waters, but contain higher proportions of HCO_3, probably through absorption of CO_2 diffusing from deeper level into peripheral groundwater,

None of the waters actually plots in the field marked "mature" suggesting that caution has to be exercised in the evaluation of deeper water-rock equilibration conditions by use of solute geothermometers. Two geothermometers responding with similar speed and comparatively fast are those based on silica and K and Mg contents of thermal water discharges (Giggenbach, 1987). They provide information on deep temperatures only for waters rising very fast. For waters rising only slowly, or residing at shallow levels for considerable time, silica and K-Mg contents are likely to reflect temperatures of water-rock interaction prevailing at shallow levels. In Fig. 3, values of $\log c_{SiO_2}$ are plotted versus $\log(c_K^2/c_{Mg})$, where c_i are the concentrations of the species i in mg/kg as listed in Table 1. The temperature dependences of the concentration quotients are those given by Giggenbach (1987, 1991).

Data points for the predominantly Cl waters (such as A1, A2, D1, and D2) plot close to the "full equilibrium" line correspondig to simultaneous attainment of equilibrium of all three species with either chalcedony *or* clays at comparatively low temperatures from 100 to 135°C. Data points for all the less mature acid, or high **SO4** waters are shifted towards the line marked "amorphous silica" suggesting that silica contents are controlled by a more highly soluble silica polymorph. Based purely on silica and K-Mg contents, only very low temperatures are suggested for the Paraso geothermal field.

A geothermometer generally providing information on deeper water-rock interaction conditions is that based on K/Na ratios of thermal waters. The most convenient way for the simultaneous evaluation of water-rock equilibration temperatures and the "maturity" of thermal waters is based on a triangular diagram involving relative Na, K and Mg contents (Giggenbach, 1987).

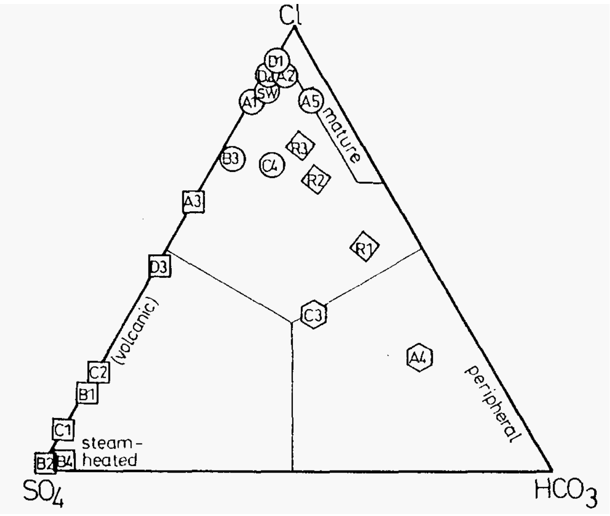

Figure 2 Classification of waters from the Paraso geothermal field on the basis of relative Cl, SO_4 and HCO_3 contents, in mg/kg.

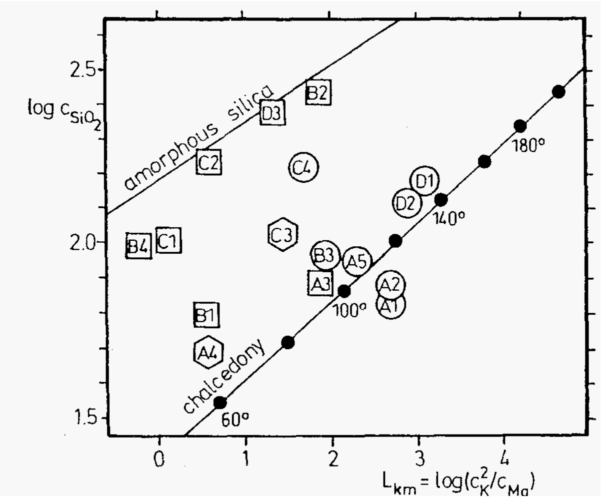

Figure 3 Evaluation of SiO_2 and K-Mg equilibration temperatures. For symbols see Table 1 and Fig. 2.

This type of diagram is most suitable in the evaluation of water compositions from highly mature high temperature systems. As indicated by Figs 2 and 3, the Paraso waters are generally highly immature. In this case more detailed information on possible processes having affected the waters is obtained by use of a square diagram based on relative Na, K, Mg and Ca contents (Giggenbach, 1987), as shown in Fig. 4.

None of the data points plots even close to the full equilibrium line. Again, those representing the high Cl waters A1, A2, D1 and D2, however, approach it most closely. Two temperatures can be read off the diagrams as indicated by the two arrowed lines emanating from the position of the four high Cl waters: relative Mg/Ca contents correspond to temperatures close to those measured or indicated by silica and K-Mg contents (Fig. 2), relative K-Na contents suggest deep water-rock equilibration temperatures of about 290°C. In view of the low degree of maturity of even the high Cl waters, these high temperatures can only be considered a preliminary indication to be substantiated by additional evidence. All the less mature waters plot at Mg/Ca ratios close to those expected for the dissolution of average crustal rock ("rock dissolution), along **a** trend suggesting uptake of **K in** secondary clays rather than addition of seawater (SW). The position of the data points representing highly immature waters confirms that their compositions are largely governed by the interaction of acid waters, formed through absorption and oxidation of H_2S, with primary rock and secondary minerals, under close to surface conditions. Samples AI, A2, D1 and D2 appear to be least affected by these processes and may, therefore, provide information on deeper water-rock interaction conditions.

The "conservative" components Li, B and Cl are generally only little affected by shallow processes. They may be used to check on the common origin of discharge waters or the occurrence of secondary processes, such as uptake of Li in secondary quartz (Goguel, 1983) or transport of B in a high temperature vapor phase (Glover, 1988). Relative Cl, Li and B contents are plotted in Fig. 5. Again, high Cl waters from all four groups occupy a distinct area suggesting a common origin. As generally observed (Giggenbach, 1989), relative Li contents of the waters are much lower than those of crustal rocks ("rock") suggesting uptake of Li in secondary minerals (quartz), or that rock leaching is of only of minor importance. B/Cl weight ratios are close to those of igneous rocks of 0.03±0.015 and suggest derivation through interaction with intrusive material at depth. Some of the less mature, group C waters show highly increased B contents, probably through absorption of high temperature vapors into waters feeding this part of the system.

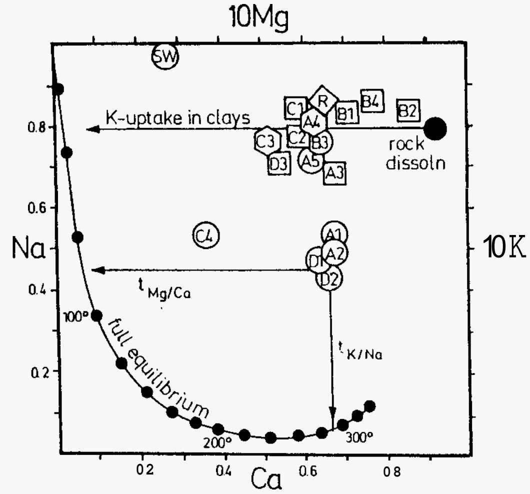

Figure 4 Evaluation of Na-K-Mg-Ca equilibration temperatures by use of values of $10c_K/(10c_K + c_{Na})$ versus $10c_{Mg}/(10c_{Mg} + c_{Ca})$, c_i in mg/kg.

Summing up, the composition of waters discharged from pools and springs at Paraso is dominated by that of acid solutions formed through aborption of deeper vapors and their interaction with rock at shallow levels. Relative K-Na contents of the highest Cl waters suggest deep temperatures of 290°C. Relative Cl, Li and B contents indicate a common origin of the deep waters, increased contents in some of the SO4 waters points to the transport of B with high temperature vapors to shallow levels.

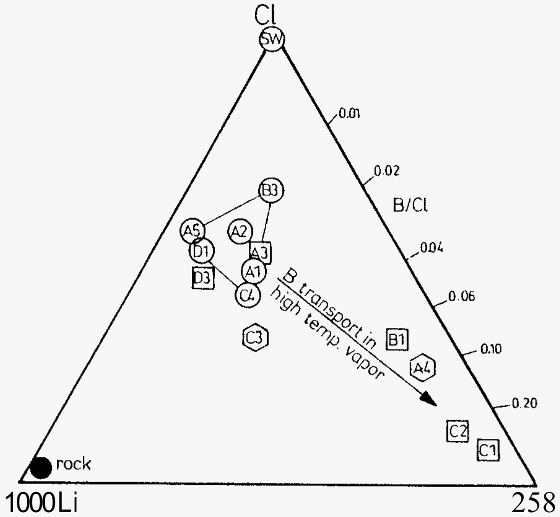

Figure 5 Relative Cl, Li and B contents, in mg/kg.

ISOTOPIC COMPOSITION OF WATERS

The isotopic composition of water samples collected in March 1977 are given in Table 2, together with flow, a short description **of** the feature sampled, and the isotopic composition of dissolved SO_4 and H_2S. In Fig. 6A, δ^2H values are plotted versus ^{18}O values. Data points for all samples plot close to a straight line extending from the composition of the river samples (R) on the meteoric water line to the isotopically most enriched, high SO_4, low Cl sample C1. There are no obvious differences in the trends shown by predominantly Cl or SO4 waters.

Major differences, however, become apparent when Cl and SO_4 contents are plotted versus ^{18}O contents (Fig, 6R and 6C). The highest shifted water is the low CI, high SO_4 sample C1. The high enrichment there is obviously due to non-equilibrium evaporation from a steam-heated pool (Giggenbach and Stewart, 1982). The same process is likely to have affected samples B4 and **C3.** The comparatively high Cl contents of the SO_4, and therefore also steam-heated waters A3 and **D3** are likely to be due to admixture of varying proportions of high Cl water. The three highest Cl waters A1, AS and D1 occupy quite disparate positions suggesting that their chemical and isotopic evolution corresponds to a more complex, than a simple mixing process involving only two endmember components.

In spite of thesse complexities, an attempt is made to evaluate the composition of a deep, high Cl parent water by use of techniques described by Giggenbach and Stewart (1982) and by assuming the isotopic composition of C1 to be due to absorption of steam having separated from such a deep parent water. In this case, the potential compositions of the steam heating pool C1 correspond to the line marked "steam heating pools". Assuming this steam to have separated at temperatures of about 230°C, the compositions of potential parent waters corresponds to the line marked "parent waters". The actual composition of this parent water may then be obtained by assuming it to represent a mixture of "andesitic water" (and. w.) (Giggenbach, 1992) and local groundwater. The corresponding point is marked (PW). Its $\delta^{18}O$ value of close to 0‰ suggests the presence of about 40% of andesitic water.

Table 2- Isotopic composition of waters, dissolved sulfate and H_2S from the Paraso Geothermal Field, in ‰, together with flow, in kg/s, and short description of sampling point.

No	t (°C)	flow (kg/s)	diam. (m)	Short Description	6^2H H_2O	$\delta^{18}O$ H_2O	$\delta^{18}O$ SO_4	$6^{34}S$ SO_4	$6^{34}S$ H_2S
A1	83	1.5	10.0	Grey, vig. "boiling"	-12.4	+3.57	-	-	-
A3	92	0.2	0.8	Vig. boiling, 5m from A1	-13.1	+2.29	+11.2	-0.8	+0.2
A4	30	1.5	0.2	Cold spring into A1	-36.4	-5.75	-	-	-
A5	46	5.0	20.0	Flow from "sizzling flat"	-40.5	-5.59	-	-	-
B1	39	2.0	12.0	Flow from "sizzling flat"	-38.2	-5.03	-		
B4	97	1.5	3.0	Vig. boiling, turbid	-17.7	+1.08	+4.1	-1.0	+0.1
C1	92	1.0	6.0	Grey, ebullition to 0.5m	+10.0	t10.60	t14.1	-	+0.2
c3	93	0.2	0.7	Vig. boiling, 3m from C1	-17.2	to.99	-		
D1	56	5.0	0.7	Clear thermal spring	-27.7	-1.50	-		
D3	86	0.2	1.5	Boiling, 0.6m above D1	-12.6	t3.51	t10.4	t14.3	-0.4
R1	30	-	8.0	Ulo River South	-38.1	-5.96	-	-	-
R2	27	600	10.0	Ngokosole River, North	-38.2	-6.00	-		
R3	34	1200	8.0	Ulo River, North	-36.2	-5.43	-		

Assuming sample D1 to be most closely related to this deep parent water, its Cl content may be obtained by extrapolating the line linking local groundwaters and D1 to a δ18O value of 0‰. According to Fig. 6B, it corresponds to about 3000 mg/kg.

As in Fig. 6B, the distribution of data points in Fig. 6C cannot be explained in terms of simple mixing processes. The variations in SO4 contents with isotopic enrichment of the steam-heated pools points to considerable variations in the H_2S contents of the steam heating these pools. Again by use of techniques described by Giggenbach and Stewart (1982), a relation may be derived allowing the degrees of enrichment in ^{18}O (Δ_{sh}, in ‰) and SO4 (c_{SO4}, in mg/kg) to be related to the H_2S content (X_{H_2S}, in mmol/mol) of the vapor heating the pool, according to

$$\Delta_{sh} = (\Delta_{pw} + 14)/(1 + 5333X_{H_2S}/c_{SO_4}) \qquad (1)$$

where Δ_{pw} is the difference in ^{18}O content between meteoric and parent water, about 6‰. In Fig. 6C, three curves are given representing variations in c_{SO_4} as a function of $\delta^{18}O$ and X_{H_2S}. It appears that pools D3, B4 and possibly A3 are heated by steam with a much higher H_2S content of close to 0.1 mmol/mol than

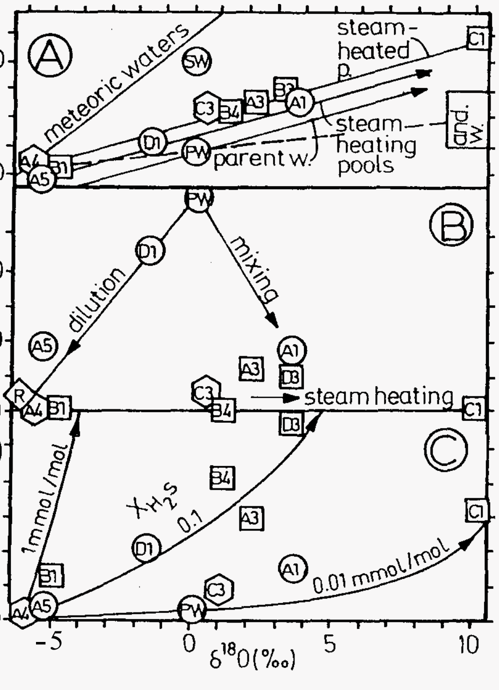

Figure 6 Plots of δ^2H (A), c_{Cl} (B) and c_{SO_4}(C) versus $\delta^{18}O$. **For** explanation, see text.

that of 0.01 mmol/mol for pools A1 and C1. The main reasons for these large apparent differences in H_2S contents are differences in the temperature of the vapors injected into the pools. Partial condensation of the rising vapors, e. g. through contact with cooler groundwaters, will lead to significant increases in gas and, therefore, H_2S contents of the rising vapors. On the other hand, secondary condensation process would also lead to the effective removal of highly water soluble constituents, such as B. According to this explanation, the vapors heating pool C1 are likely to be least affected by secondary condensation process, in full agreement with the high B content of this pool (Fig. 5).

The assumption that the SO_4 of the waters is largely formed through air oxidation of H_2S within the pools themselves is strongly supported by the very small fractionation of ^{34}S between dissolved sulfate and H_2S for samples A3 and B4, as given in Table 2. For sample D3, the difference in $\delta^{34}S$ values of about 14‰ would correspond to an equilibration temperature of about 400°C (Robinson, 1987), but may be due to mixing of a non-equilibrated with partially equilibrated waters. The fractionation of ^{18}O between SO4 and pool water corresponds to reasonable equilibration temperatures of between 200 (A3) to 320°C (B4, C1). The strong dependence of the isotopic composition of SO4 on that of the pool waters, however, suggests that the SO4 formed again under close to surface conditions, in contact with waters already affected by surface evaporation. Assuming equilibration with the deep parent water, with a $\delta^{18}O$ value of 0‰, considerably lower temperatures of between 130 (C1) to 300°C (B4) would be indicated, even lower temperatures of 80 (C1) to 180°C (B4) for equilibrium with local meteoric water (-6‰).

Variations in the isotopic and chemical composition of thermal waters from the Paraso geothermal field show that they are affected by a variety of shallow mixing and vapor absorption processes greatly impeding the application of standard geochemical exploration techniques. On the basis of an integrated approach, the deep parent water may contain about 3000 mg/kg of Cl, at a temperature of close to 290°C. Its inferred isotopic composition (δ^2H = -32‰, $\delta^{18}O$ = 0‰) would correspond to an "oxygen-shift" by about 6‰, or the presence of about 40% of "andesitic water". The large variability in chemical and isotopic compositions, and the absence of clear compositional trends, are likely to be due to the overlap of generally widely separated major upflow zones of liquid and vapor within a small discharge area.

CHEMICAL AND ISOTOPIC COMPOSITION OF GASES

Because of the generally low discharge temperatures, water contents of the vapors sampled at Paraso are highly variable and bear only little resemblance to those at deeper levels. The compositions of gases, therefore, are reported in Table 3 in mmol/mol on a dry basis. Recently a variety of techniques has

Table 3- Chemical composition of gases, in mmol/mol, together with isotopic compositions of CO_2, CH_4 and H_2, in ‰.

No	CO_2	H_2S	NH_3	He	H_2	Ar	O_2	N_2	CH_4	$\delta^{13}C$ CO_2	$\delta^{13}C$ CH_4	$6^{2}H$ CH_4	$6^{2}H$ H_2
A3	966	19.8	0.02	0.011	2.5	0.13	<.002	8.6	2.8	-0.8	-3.5	-124	-449
A5	967	19.2	0.04	0.021	3.4	0.11	<.002	6.7	3.6	**-0.8**	-3.4	-143	-447
B4	968	20.4	<.01	0.013	3.0	0.05	<.004	4.2	4.7	-0.7	-3.7	-135	-479
C1	971	17.2	<.01	0.016	4.2	0.07	<.006	5.7	2.3				
C3	974	17.2	0.03	0.010	4.4	0.03	<.002	2.7	2.1	-0.5	-4.0	-124	-451
D3	977	12.9	<.01	0.005	3.5	0.10	<.002	6.2	0.8				

been reported allowing the evaluation of deeper gas equilibration conditions on the basis of simple ratios, such as CH_4/CO_2, CO_2/Ar or H_2/Ar (Giggenbach, 1991). The approach taken here corresponds to that used in a discussion of reactions controlling redox conditions in possibly highly immature systems (Giggenbach, 1993) and is based on plots of $R_{MC} = \log(x_{CH_4}/x_{CO_2})$ versus $R_{HA} = \log(x_{H_2}/x_{Ar})$, as shown in Fig. 7.

Three theoretical curves are given, each representing potential redox systems governing equilibration among the species CO_2, H_2 and CH_4. The one marked "calc.-anh." (calcite-anhydrite) corresponds to control of redox potentials by the coexistence of these two minerals at CO_2/H_2S ratios of 100. Variations in CO_2/H_2S ratios have only a very minor effect on the position of this line. The two remaining curves are marked "rock buffer" and represent redox control by Fe(II) and Fe(III) of the rock matrix with the gases dissolved in a single "liquid" phase or present in a "vapor" phase. The distribution of data points for the Paraso gases clearly suggests equilibration under redox conditions close to those of the "rock buffer", and in a liquid phase, at temperatures close to 310°C. This temperature agrees closely with that suggested by K/Na ratios (Fig. 4). Homogenous fluid phase CO_2, CH_4, H_2, Ar equilibration teniperatures, t_{MCA} in °C, may be evaluated directly by use of the relation

$$t_{MCA} = 180 + 13.3\log(x_{CO_2}/x_{CH_4}) + 53.3\log(x_{H_2}/x_{Ar}) \quad (2)$$

It is valid from 100 to 340°C and for equilibration in a single liquid phase. The temperatures obtained by use of the data reported in Table 3 range from 282 to 331°C, with a mean of 304°C.

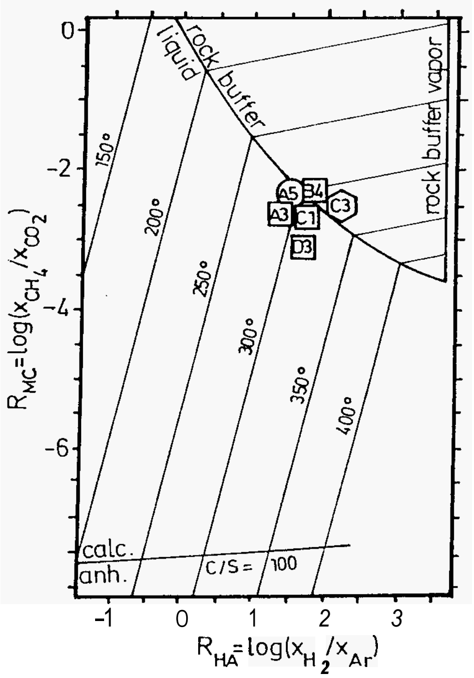

Figure 7 Evaluation of CH_4-CO_2 and H_2-Ar equilibration temperatures.

The differences in the ^{13}C contents between CH_4 and CO_2 are with 3.0±0.4‰ far below that expected for equilibrium at 300°C of about 25‰ (Lyon and Hulston, 1984). The $\delta^{13}C$ values of both the CO_2 and CH_4 are well above those generally encountered in geotherinal gas discharges. Those of CO_2 fall into a range typical of marine limestone, the extremely high values of the CH_4 may be the result of bacterial oxidation within the pools (Coleman *et al.*, 1981). In view of the very fast rate of passage of gases through most of the pools at Paraso, such an explanation appears unlikely. At present the most likely explanation is rapid, inorganic formation of CH_4 under conditions allowing it to approach closely chemical, but not isotopic equilibrium. The fractionations of ^2H between CH_4 and H_2 and between H_2 and H_2O correspond to temperatures of 220 to 260°C, a range spanning that typical of vapor-dominated systems.

A useful indicator of the origin of geothermal fluids is based on relative N_2, He and Ar contents, as shown in Fig. 8. The chemical composition of gases from geothermal and volcanic systems as a function of tectonic setting, can be interpreted in terms of several endmembers (Giggenbach, 1992): a very low He, meteoric component with N_2/Ar ratios between those of air (38) and air saturated groundwater, asw, (83); an "andesitic" component, generally associated with gases discharged along convergent plate boundaries, with N_2/Ar ratios well above those of the meteoric component; and two components characterised by high relative He contents, a crustal one with He/Ar ratios close to unity and a non-arc basaltic component derived essentially from the mantle with close to meteoric N_2/Ar ratios.

Data points for Paraso plot along a line linking meteoric gases to high He, either crustal or mantle gases. A distinction between the two is possible on the basis of the $^3He/^4He$ ratio, at present not available. Taking into account the general tectonic and geological setting of the Paraso field, the position of the data points would suggest an essentially mantle origin of the gases little affected by the addition of volatiles derived from subducted marine sediments. This conclusion is supported by the low CO_2/He ratio of 75 000 and N_2/He ratio of 450 resembling much more "basaltic", rather than "andesitic" gases (Giggenbach, 1992).

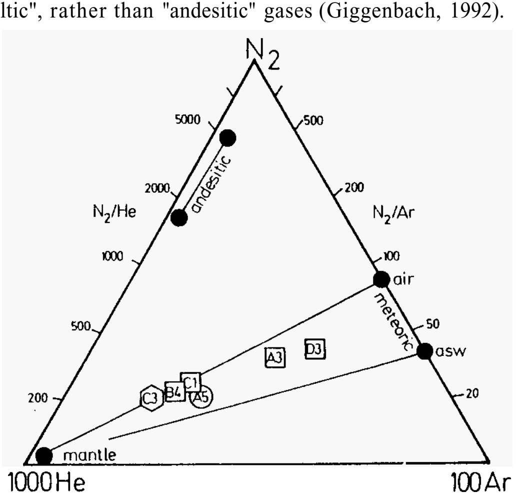

Figure 8 Relative N_2, He and Ar contents of gas discharges from the Paraso geothermal field, on molar basis

Summing up findings based on the chemical and isotopic compositions of the gas discharges, the Paraso field is likely to house a high temperature system with temperatures over the major storage zones of the older of 300°C. The gases are likely to have equilibrated both with rock and internally while dissolved in a liquid phase. Low ratios of CO_2/He and N_2/He, and the $\delta^{34}S$ value of H_2S resemble more closely those of mantle volatiles, rather than gases associated with subduction zones.

SUMMARY AND CONCLUSIONS

At first inspection, the Paraso geothermal field shows all the characteristics of **a** major vapor discharge area: absence of clear pools and silica deposits, the presence of vigorously "boiling", turbid pools, mudpools and of hydrothermal alteration typical of interaction with acid waters. Only chemical analysis reveals the discharge of neutral, comparatively high Cl waters typical of a mature, high temperature, liquid dominated geothermal system. Even these high Cl waters, however, are to varying degrees contaminated with obviously less mature waters rendering application of standard geochemical techniques in their interpretation difficult. Under these circumstances, only the "slowest" indicator systems are likely to preserve information from deeper levels, in this case it is the K/Na ratio which suggests deeper temperatures of 290°C. The high rates of discharge of the gases preserves deeper equilibration compositions and gas geothermometers indicate internally consistent temperatures of close to 300°C.

Based on the isotopic and chemical composition of the waters, a Cl content of the deep parent water of 3000 mg kg was derived. At a temperature of 300°C, the heat equivalent of Cl corresponds to 0.45 MJ/g of Cl. Assuming all Cl discharged from the area to end up in the *two* rivers draining the area, their flows correspond to a Cl discharge rate of close to 400 g/s or a natural heat discharge of 180 MW. This evaluation assumes that all the vapor released from the system is derived from the 300°C parent water.

In geothermal systems in regions of high topographic relief, areas of vapor discharge are generally located at higher elevations and well separated from the discharge of associated neutral Cl waters at lower levels, as e. g. clearly demonstrated by three geothermal areas over the Guanacaste Geothermal Province in Costa Rica (Giggenbach and Corrales, 1992). The juxtaposition, or even overlap of vapor and liquid discharge areas at the Paraso geothermal field is likely to be due to its position in a narrow valley and close to sealevel, focussing the discharge of both vapor and liquid, having separated at deeper levels, into a small area. The rapid rise of copious quantities of vapor at Paraso points **to** the existence of extensive vapor-dominated zones, or a vapor "chimney", as described in detail for the "vapor-cored" geothermal system of Alto Peak, Philippines (Reyes ***et** al.,* 1993). There, deep drilling encountered a several km high vertical zone occupied by vapor, surrounded by an envelope of neutral, high Cl waters. Surface manifestations there closely resemble those at Paraso; due to its position, high on **a** dormant volcano, Cl is absent in the pool waters at Alto Peak.

The composition of rocks making up the island of Vella Lavella, ranges from pyroxene basalt to younger hornblede andesite (Taylor, 1976) and is common for magmas produced along convergent plate boundaries. Low ratios of CO_2/He and N_2/He, and the isotopic composition of H_2S ($\delta^{34}S = 0‰$), however, resemble more closely those of mantle derived gases. Also, the $\delta^{13}C$ values of both CO_2 and CH_4 are with about -0.7±0.2‰ and -3.7±0.2‰ far above those encountered e. g. in New Zealand geothermal systems (Lyon and Hulston, 1984). Similar high values (CO_2: -1‰; CH_4: -8.5%) in deep-sea hydrothermal fluids from the southern parts of the Izu-Bonin and Mariana arcs were recently ascribed to the extraordinarily thin and young crust there and the absence of old sediments (Tsunogai *et al.,* 1994). According to Furumoto *et al.,* (1970), the depth to the mantle, in th Vella Lavella region of the Solomon Islands, is only 8 km.

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